

# **Development of a Damage Tolerant Truss based Composite Empennage Box**

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**Truss structures are widely used for the support of structural loads in applications where minimum mass solutions are desired. Ideally these truss structure are made out of bars hinged at the ends to transfer axial forces and moments. Truss structures provide high stiffness and strength to weight ratio. In this study, this concept is considered towards the realization of a truss based empennage of an aircraft. A three dimensional composite truss box is designed to replace a conventional empennage interspar box without sacrificing stiffness and strength. Several co-cured truss elements were fabricated. Simple tests conducted on these truss elements indicate that one-to-one stiffness matching can be achieved between conventional and truss-based structure. However, further design changes are needed to match their specific strength. Weight savings of about 15% is expected through the use of truss based design concepts.**

## **I. Introduction**

Composite aircraft structural components such as empennage are nowadays mostly made of typical skin- rib- stiffener constructions where the ribs and spars are of full depth. The mechanical properties of composites are not fully exploited in these type of construction. In view of this it is very necessary to examine new structural concepts which not only exploit the properties of composites better but also built in damage tolerant features into the aircraft structure. This paper reports in details the design approach, analysis and fabrication methods of a conventional box and an equivalent truss box of a typical civil aircraft. Experiments were conducted to make one-to-one comparison between conventional and truss spar segments of the empennage box. Several promising fabrication techniques are studied to find the optimal way of fabricating aerospace quality truss based structural joints. A typical empennage box is taken as a numerical case study for reduction in structural weight by replacing conventional spar and ribs with truss concepts. Skin, spars and stringers are the main loading carrying members in the empennage box, while the ribs contribute only a little to the overall stiffness of the empennage box.

Truss based structures provide opportunity to minimize weight by transferring loads effectively within the structure. In particular, they present an attractive option for structural elements such as ribs and spars which are primarily designed to carry compressive and shear loads. If truss elements are used instead of a conventional web in a spar, the shear load acting on the spar can be effectively diffused as axial loads on the truss elements. Intuitively, this appears to be a more effective and efficient approach to carry the shear loads instead of a full web on a conventional segment

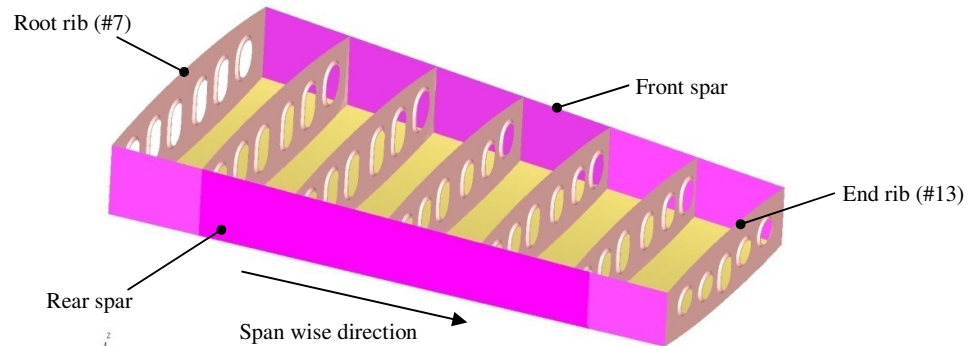
Krog et al [1], conducted topology optimization of the A380 wing box to reduce rib weight. Ref. [2] Sierakowski et al explains the need for damage tolerant design in composites compared to metals. Two major criteria in selecting a damage tolerant design are: (a) Identification of the most severe and common form of loading event, which results in damage that is structurally unacceptable, and (b) Identification of the resulting failure mode associated with that damage which leads to good damage tolerant design. Ozden et al [3] carried out integrated testing and analytical studies on damage tolerance of Graphite/epoxy composite tubes under compressive loading. Swanson et al [4] conducted experimental studies and developed mathematical models of triaxial composite tubes under two dimensional loading. The braided material shows somewhat reduction in strength in axial direction. Analysis of the microstructure indicates that stiffness variations in the transverse direction occur, because of the discrete axial yarns. These stiffness variations are believed to cause strain concentrations that contribute to the low braid failure strains. Ayranci et al [5] studied the advantages and disadvantages of 2D braided technology over stiffness and manufacturing process. Currently, several researchers are studying composite truss joints which form an important part in such structures, and their load transfer capacity and efficiency.

Braided composites are capable of handling shear and torsional loads effectively. Braided preform cured with matrix system either by Resin Transfer Molding (RTM) method or by prepreg technology can be used as load carrying members. They offer increased transverse moduli, transverse strength, damage tolerance, dimensional stability and near net shape manufacturing capabilities. Damage tolerance is a consequence of the locking mechanism between the intertwined fibers of the braided architecture that prevents or limits yarn delimitations.

## **II. Composite Empennage Box**

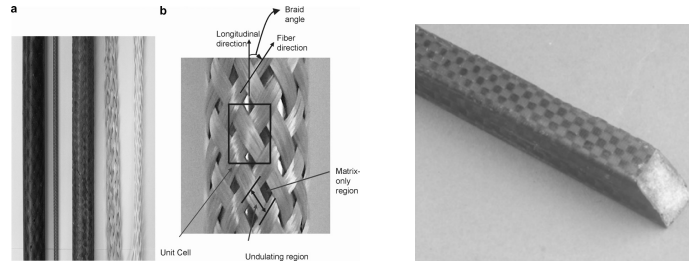
A typical civil aircraft empennage inter spar section box of size (2000mm\* 1500mm \* 350mm) made out of CFRP composites was considered in this study towards replacement of conventional spar and ribs with truss elements. Empennage is an aviation term used to describe the tail section of an aircraft. The inter spar box is the

primary load carrying member. A typical inter-spar box consists of a front spar, rear spar and two stringer skin panels on the top and bottom. Fig [1] shows internal view of sectional box with conventional spars with full web and ribs with cutouts. The sectional box considered in this study has two spars and seven ribs (#7 - #13). The objective of this work is to replace the five interior ribs and two spars by elements made of truss construction without compromising the stiffness/strength of the box.



**Fig [1]. Typical section of empennage box with conventional ribs**

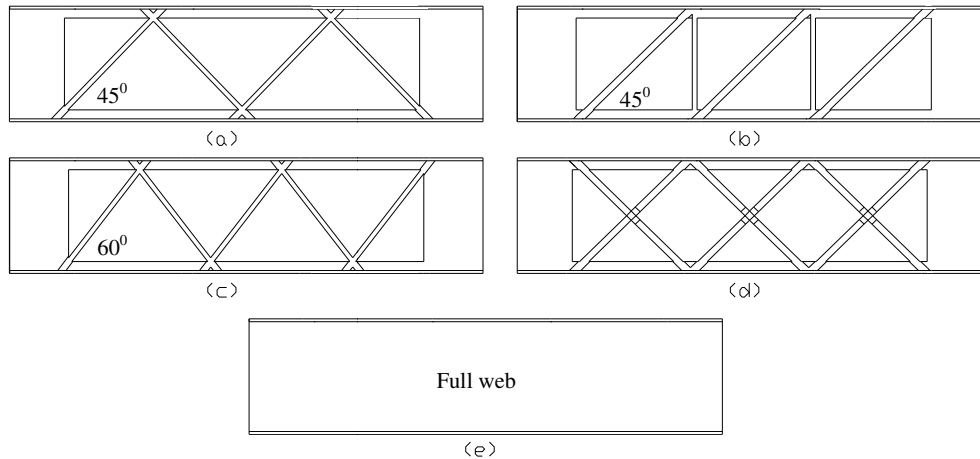
The CAD weight of the conventional box is 28.41 kg: spars weigh about 11%, and ribs together weigh about 10% of the total box weight. Structurally, spars webs resist shear force and ribs contribute to contouring, torsional stiffness and sectioning of skin panels to increase buckling strength. Introducing a truss based sub-structure is expected to reduce the weight of empennage box. Since truss elements mostly carry pure axial loads, they are expected to be more efficient compared to a conventional web carrying shear loads. Truss concepts can be realized by introducing braided composite elements which are weaved in circular fashion with  $\pm 45^\circ$  (mostly) degree and  $0^\circ$  degree fiber orientations (Figure 2). They can be made into structural members by curing them either through wet-layup or resin transfer molding process. Braiding is a preform manufacturing technique to interlace the fibers tows in circular or desired shape using a braiding machine. A 2d braided preform has fibers running in axial and transverse direction (Fig 2). Braided materials usually exhibit some loss of in-plane stiffness and strength relative to conventional laminates, particularly in the braid fibers because of the undulating fiber path. However, very little information is available in literature to assess the trade-offs in properties. In the present study, the braids are made using bidirectional carbon fabric to form a sandwich truss element.



**Fig [2]. 2D Braided Composite**

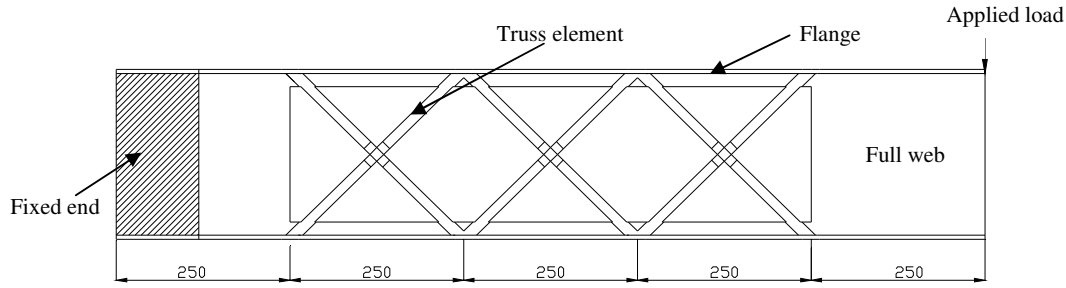
### III. Study on conventional and truss-based spar

The rigidity of the empennage box mainly depends on spars running along the span wise direction. As a first step, 4 different truss-based spar constructions were considered based on a literature survey and their performance were examined (Fig [3]). The joints are assumed to be rigid so as to transfer bending/torsional moments. The selection of best configuration is based on Finite Element Analysis (FEA) approach. The stiffness-to-weight ratio and strength-to-weight ratio were the parameters considered.



**Fig [3]. (a) Config A: truss elements at  $45^\circ$  orientation, (b) Config B: truss elements with  $45^\circ$  and vertical mem, (c) Config C: truss elements at  $60^\circ$  (d) Config D: truss elements crossing at  $45^\circ$  (e) Conventional spar**

The segments were modeled as I-section with dimension 1200mm\*300mm\*50mm. The two ends of the I-section were modeled as full web to avoid edge effects. A typical section is shown in Fig [4]. The flange and a portion of web were modeled in NASTRAN using CQUAD4 element with PCOMP property card. The material properties of flange and portion of the web are presented in Table [1]. The laminate sequence is  $[45/-45/0/90/0/45/0/-45/90]_s$ . The truss elements were modeled as one-dimensional CBAR element. Since property of braided composite elements was not fully established at the time of this study, the truss elements were assigned isotropic material properties. The truss elements have square cross-section with 12mm width and wall thickness 1.5mm. All 5 configurations were loaded as cantilever beams with concentrated tip load of 1kN.



**Fig[4] Config D truss spar segment**

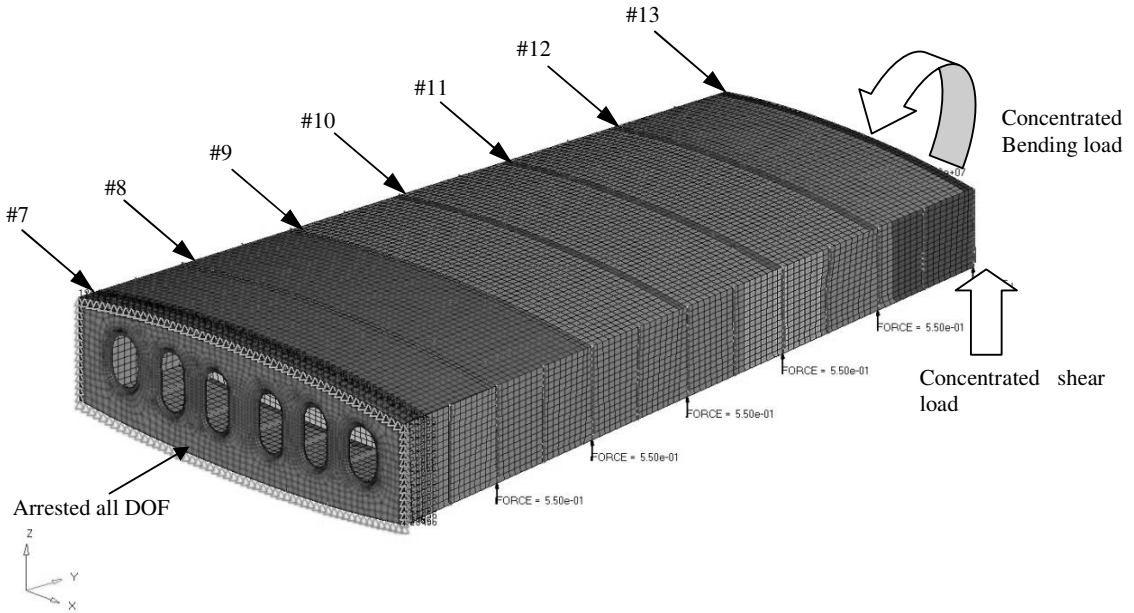
**Table [1]. Properties of CFRP Laminate**

$E_{11}$	$E_{22}$	$G_{12}$	$\nu_{12}$	$X_t$	$X_c$	$S$
105 GPa	6 GPa	5.1 GPa	0.32	1300 MPa	950 MPa	46 MPa

#### **IV. Study on conventional and truss based rib**

##### **A. Analysis of truss ribs**

In this section, only the conventional ribs of the empennage section box were replaced with truss ribs. The rib locations are shown Fig [5] with defined boundary locations. The spars and skins were modeled in NASTRAN using CQUAD4 element with PCOMP laminate properties. The truss elements were modeled as one-dimensional CBAR element and were assigned isotropic material property. Square section of tube is 12mm width and wall thickness 1.5mm. The empennage box is analyzed for (i) shear/bending load case (ii) torque load case and (iii) buckling. Shear loads of 8 kN is applied at front and rear spars. The outboard section of the empennage box is accounted by considering the loads transferred by it to the inter-spar section box: 4000 kN shear loads applied at end rib and 380 kN-mm bending load. Rib 7 was arrested in all degrees of freedom. The conventional empennage box was modeled using ribs with cut-out. The truss empennage box was modeled with truss ribs (Configurations A, B, C and D) between stations #8 to #12.



**Fig[5]. FE model of empennage box with rib (index) location**

#### **B. Analysis of truss box**

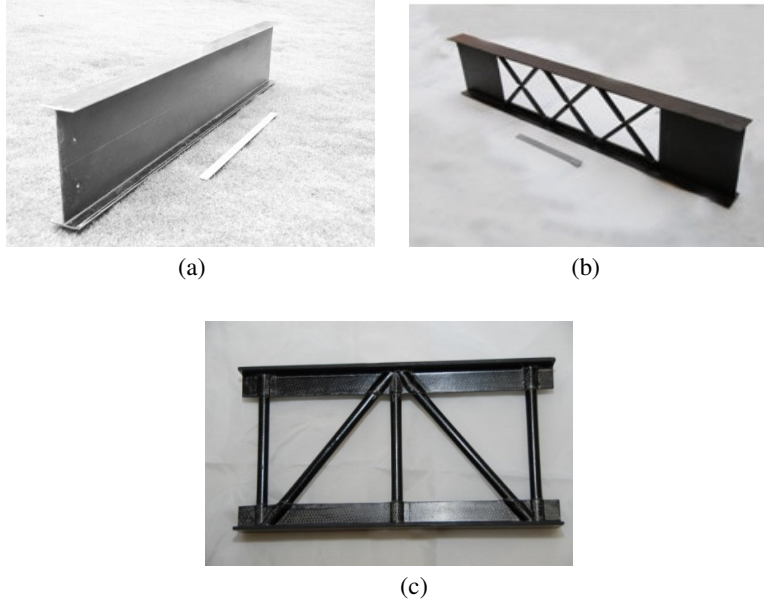
In this section, both the spars and ribs were replaced with truss configuration. To study the stiffness/strength characteristics truss configuration; box level analysis is being carried out for config D with above said boundary condition in section [A]. The modeled weight budgets of the configurations are shown in Table [2].

**Table [2]. Weight budget of various sub components of sectional box**

Sub parts	Conventional Config	Truss Config
Front and rear spar (Kg)	3.17	1.914
Truss ribs #8 to #12 (Kg)	3.02	2.02

#### **V. Fabrication of conventional/truss spar segment**

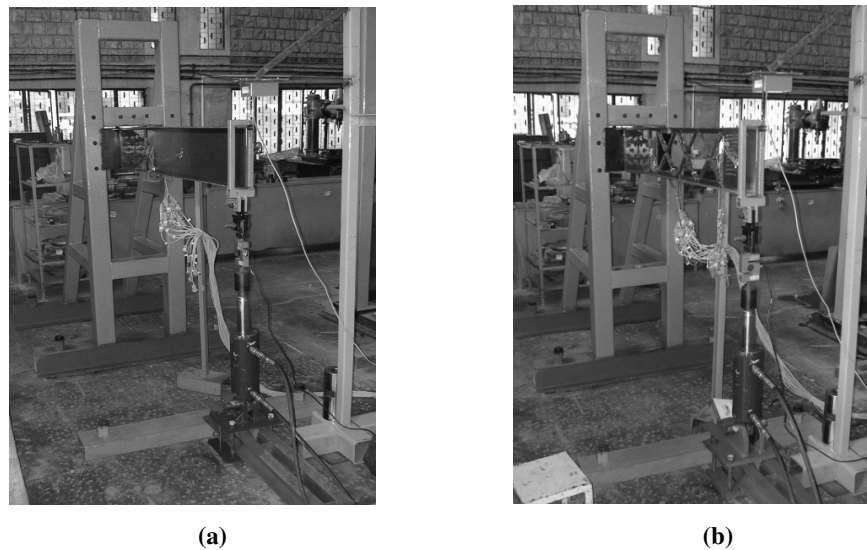
A conventional/truss structural I-section segment was fabricated using hand layup technique (1500mm\*300mm\*50mm) Fig[6]. The fabrication of truss segment is highly challenging. CFRP carbon UD/BD fabric material use to fabricate the I-sections. The truss braids preform were sandwich between foam core to retain its shape (12 mm diameter) and co-cured along with T-section. The fabricated segment shows the possible way of curing one element, two element joints and three element joints. The moulds were made out of laminated sheet of 25mm thick machined and carved to the required shape. Resin Transfer Molding (RTM) and Autoclave molding using preregs for fabrication are currently under progress. The conventional segment weighs about 2.56 Kg and truss spar segment weighs about 1.51 Kg.



**Fig[6]: (a) Conventional rib segment (b) Truss rib segment 1 (c) Truss segment 2**

## **VI. Experimental studies**

The conventional and the truss segments of the empennage box were tested with one end fixed and the other end loaded under bending to ascertain and compare the strength and stiffness of the same. The complete test setup is shown in the Fig [7].



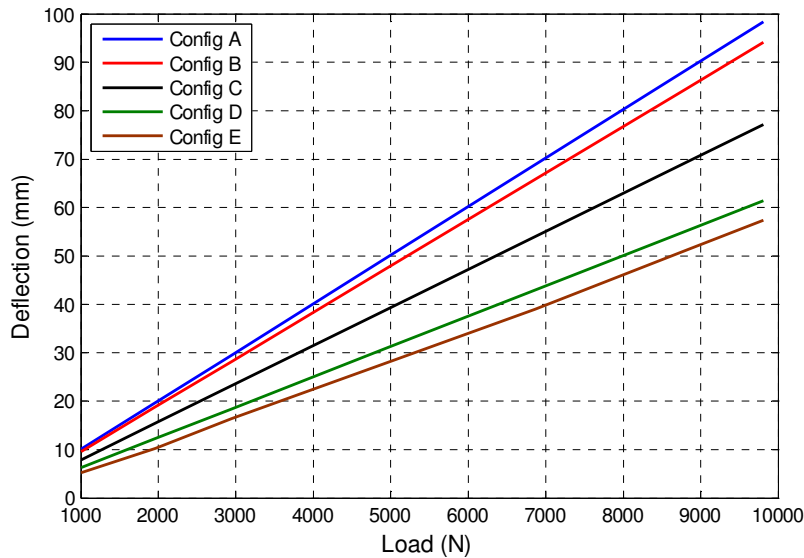
**Fig [7] (a) Conventional segment test rig (b) truss segment test rig**

An in-house test rig was designed and developed for carrying out this cantilever pull test. Test fixtures were designed to hold the test article and mount the same on to the test rig. Strain gauges were bonded at the few

critical locations especially at the flanges and web of the segment at its fixed. A lording fixture for applying the load at the other free end was developed which in turn connects to an hydraulic actuator for the load application. The strain response of the segments were monitored at the various loading steps till its failure .The tip displacement of the cantilever segment was monitored using a displacement transducer at every load step till the failure of the test specimen.

## VII. Results and discussion

(a) Stiffness characteristic of truss segments is shown in Fig [8]. The analysis is being carried to match the stiffness close to convectional full web spar. Comparatively Config D has maximum stiffness of 157.941 N/mm, where Config A has least stiffness of 99.66 N/mm, other segment stands between these two values.



**Fig[8]. Comparison of stiffness for different configurations of spars**

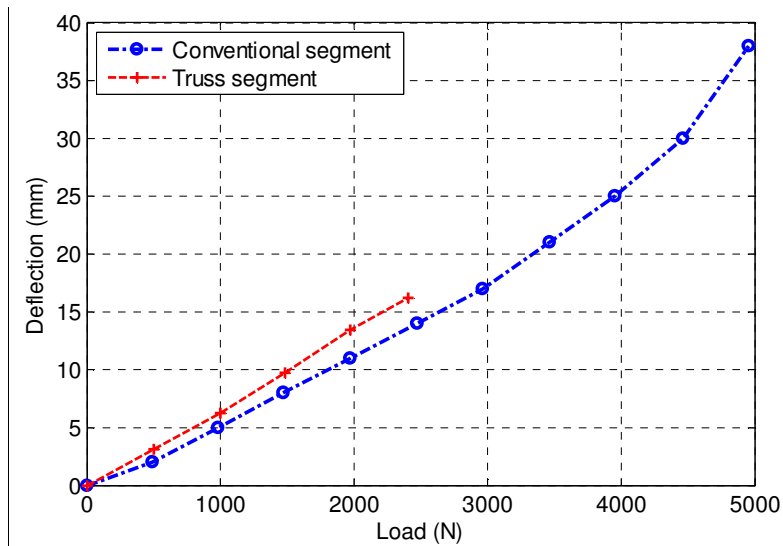
(b) Conventional rib with cut-out web were replaced with truss structure. The analysis result of empennage box is shown in Table [3]. The tip deflections of these configurations were close to conventional box. The first three buckling modes were near the root due to edge effect were not considered for tabulation. Comparatively config D has high buckling factor to conventional model but truss segment with 60° degree orientation (Config C) will be an optimum selection in terms of weight and response to load. The response to twisting torque is about 0.3° at rib#7 for all the configurations.



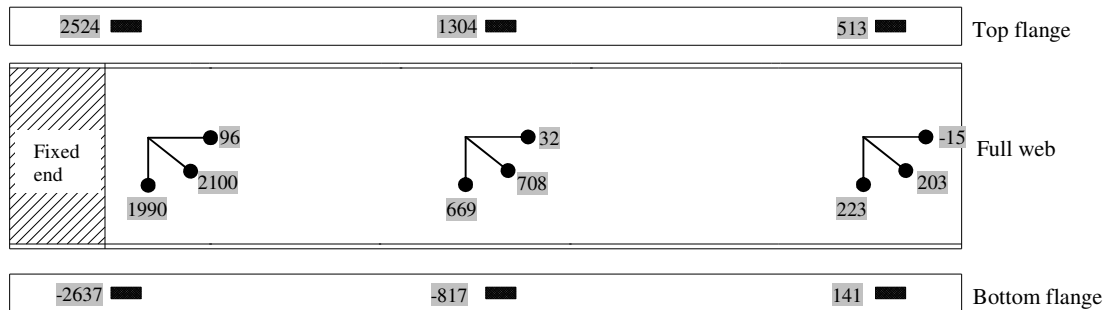
**Table [3]. Tip deflection of four empennage configurations**

	Conventioanal Box	Config - A	Config – B	Config – C	Config - D
Rib weight (Kg)	3.02	1.04	1.56	1.316	2.09
Maximum tip deflection @ Rib13 (mm)	29.86	26.39	26.98	26.7	27.4
Buckling factor (4 <sup>th</sup> mode)	0.913	0.877	0.911	0.913	0.915

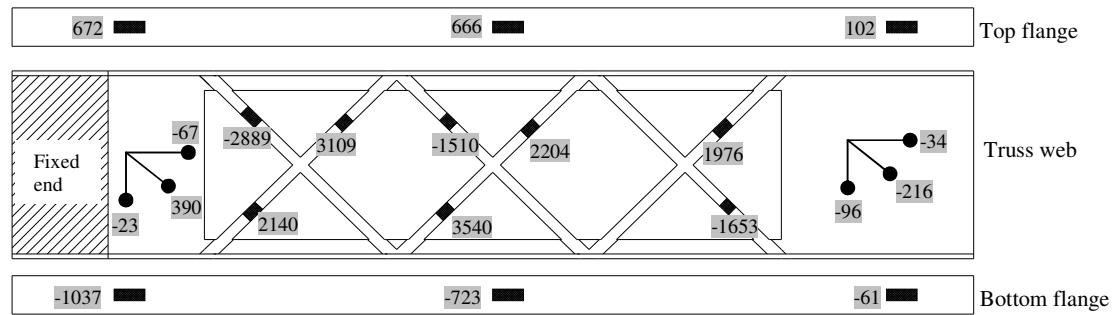
(c) The experimental results carried out on the conventional/truss spar. Both the specimens failed catastrophically. The stiffness has been calculated from slope given in Fig[9]. Conventional segment has stiffness about 170.694 N/mm and truss segment is about 147.15 N/mm. The stiffness of both the spar were closely matched. The failure load of conventional segment is 4954.05 N and the truss segment is 2403.45 N. The failure strain measured are shown in Fig[10 a, b]



**Fig[9]. Load/deflection for conventional/truss segment**



**Fig [10.a] Failure strains of conventional spar**



**Fig [10.b] Failure strains of truss spar**

## VIII. Conclusions

Segment analysis was carried for four configurations. Config D has comparatively high stiffness. A study of one to one comparison for conventional to truss box has been carried out. Weight savings up to 15% is achieved in box level analysis. The tip deflection of truss empennage box is well close with conventional box. The buckling factor of truss box matches with conventional box with a factor of 0.9. The torsional stiffness of conventional and truss box is about 0.3 degree for all the cases. Robust and low cost fabrication has been arrived to fabricate composite co-cured truss structure. Experimental studies shows good stiffness matching between conventional and truss spar segment. Weight saving upto 40% compare to conventional segment spar. Further studies are being carried out to match the strength properties. RTM/prepreg fabrication methods are under progress to meet aerospace quality.

## IX. References

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